RESEARCH MEMORANDUM

EFFECT OF CHANNEL GEOMETRY ON THE QUENCHING

OF LAMINAR FLAMES

By A. L. Berlad and A. E. Potter, Jr.

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SUMMARY

The effect of channel geometry on flame quenching, as calculated on the basis of average active particle chain lengths, is related among six different geometries: plane parallel plates of infinite extent, cylindrical tubes, rectangular slots, cylindrical annuli, and tubes of elliptical and equilaterally triangular shape.

Experimental determination of the quenching behavior of propane-air flames over an equivalence-ratio range of 0.82 to 1.30 was made for a series of rectangular slots, cylindrical annuli, and cylindrical tubes in the pressure range 0.08 to 1.0 atmosphere. Ten rectangular-slot geometries covering a length-to-width ratio range of 1:1 to 33.3:1, nine cylindrical annulus geometries covering a diameter-ratio range of 1.33:1 to 25:1, and four cylinder diameters were investigated. Generally good agreement between theory and experiment was found for both rich and lean flames. The average deviation of the predicted quenching distances from the observed ones is 4.3 percent for equivalence ratios less than or equal to unity and 8.6 percent for equivalence ratios greater than unity. These deviations are generally systematic, rather than random.

It was also found that relatively small cold surfaces may, when flame immersed, exhibit very large quenching effects.

INTRODUCTION

Recent flame-quenching research (refs. 1 and 2) has indicated that a set of simple relations should exist among the various channel geometries that are capable of just quenching a given flame at a given pressure. A relation between quenching by cylindrical tubes and by plane parallel plates was derived in reference 1 on the basis of a diffusional quenching equation. A relation between quenching by rectangular slots and plane parallel plates of infinite extent is given in reference 2. It is also indicated in reference 2 that relations among quenching geometries, which may be derived on the basis of the diffusional quenching mechanism of reference 1, may also be derived on the basis of a thermal mechanism in which flame propagation or nonpropagation is determined by some critical value of the average reaction temperature excess over that of the cold gas rather than some critical value of the average concentration of active particles in the flame. Regardless of which of these quenching mechanisms is assumed, a suitable set of such equations would make possible the prediction of the quenching effect that any of a large number of geometries will have on a given flame, once this effect is determined for any one geometry.

Thus, the objectives of this investigation were: 3249

(1) To derive a set of equations which can be used to predict the dimensional relations among a number of simple geometries that are capable of just quenching a given flame at a given pressure.

(2) To test several of these relations by experimentally determining the wall quenching of propane-air flames as a function of air-fuel ratio and pressure for rectangular slots, cylinders, and cylindrical annuli.

SYMBOLS

The following symbols are used in this report:

A	fraction of molecules present in gas phase which must react for flame to continue to propagate
a	inside annulus diameter
B_1	arbitrary constant
B_2	arbitrary constant
b_e	ellipse major axis
b_r	rectangular slot length
C_T	total number of active particles
c	numerical concentration of active particles
$\bar{c}$	average numerical concentration of active particles
c_0	number of active particles created per unit time per unit volume
D_i	diffusion coefficient for active particles of one kind
d	quenching distance
d_a	outside annulus diameter

d_c cylinder diameter

d_e minor axis of ellipse

d_p plane parallel plate separation

d_r rectangular slot width

d_t side length of equilateral triangle

G quenching geometry factor

k_i specific rate constant for reaction of active particles of one kind with fuel molecules

N_f average number of fuel molecules per unit volume of reaction zone

n power describing the temperature dependence of the diffusion coefficient, $D \propto T^n$

p pressure

r plane polar coördinate

T_0 initial burner wall temperature and temperature of unburned gas

T_R reaction temperature

ν average number of effective collisions of an active particle with gas phase molecules before the particle collides with and is destroyed at a wall

τ time between effective collisions

φ equivalence ratio

Subscripts:

a annulus

c cylinder

e ellipse

i active particle species

p plane parallel plates of infinite extent

r rectangular slot

t equilateral triangle

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THEORY

Quenching by cylindrical tubes and plane parallel plates of infinite extent. - A relation between the quenching distances associated with cylindrical tubes and plane parallel plates of infinite extent is derived in reference 1 on the basis of the diffusional quenching equation

$$d = \sqrt{\frac{A}{k_i}\left(\frac{T_R}{T_O}\right)^n \frac{G}{N_f \sum_i \left(\frac{p_i}{D_i}\right)}} \tag{1}$$

The geometric factor G was determined from the average chain-length calculations of Semenov (ref. 3). The average chain length is the average number of effective collisions of an active particle with gas phase molecules before the particle collides with and is destroyed at a wall. For the case of the cylinder, reference 3 gives

$$\nu_c = \frac{d_c^2}{32 D_i \tau_i} = \frac{d_c^2}{G_c D_i \tau_i} = \frac{\bar{c}_c}{c_O \tau_i} \tag{2}$$

For the case of plane parallel plates of infinite extent, the average chain length (ref. 3) is

$$\nu_p = \frac{d_p^2}{12 D_i \tau_i} = \frac{d_p^2}{G_p D_i \tau_i} = \frac{\bar{c}_p}{c_O \tau_i} \tag{3}$$

It follows that $\bar{c}_c = \bar{c}_p$ and $\nu_p = \nu_c$ when

$$\frac{d_p}{d_c} = \sqrt{\frac{12}{32}} \tag{4}$$

Equation (4) is the relation between these two quenching geometries when either is capable of just quenching a given flame.

It is significant to note that the assumption that all terms other than G on the right side of equation (1) are unchanged by a change in geometry gives rise to a constant dimensional relation between d_p and d_c (eq. (4)) and implies that other such relations should exist among other quenching geometries.

Quenching by rectangular slots. - In order to calculate the flame-quenching effects of rectangular channels, assuming the same type of diffusion mechanism employed in reference 1, one may proceed by first

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solving the diffusion equation subject to the appropriate boundary conditions. Thus, consider a rectangle with center at the origin of the x,y plane. The rectangle is of length b_r and of width d_r (fig. 1(c)). Let this rectangle correspond to a typical cross section of a rectangular channel of infinite extent in which active particles are being generated uniformly throughout the volume and destroyed on collision with the walls. The differential equation of diffusion describing this case is

$$\frac{\partial^2 c_r}{\partial x^2} + \frac{\partial^2 c_r}{\partial y^2} = - \frac{c_0}{D_i} \tag{5}$$

subject to the boundary conditions

$$c_r = 0 \qquad \text{at} \quad \begin{Bmatrix} x = \pm b_r/2 \\ y = y \end{Bmatrix} \tag{6a}$$

and

$$c_r = 0 \qquad \text{at} \quad \begin{Bmatrix} x = x \\ y = \pm d_r/2 \end{Bmatrix} \tag{6b}$$

If a unit height is considered, the total number of active particles in the rectangular channel $C_{T,r}$ is given by

$$C_{T,r} = 4 \int_0^{d_r/2} \int_0^{b_r/2} c_r \, dx \, dy = \bar{c}_r b_r d_r \tag{7}$$

An equation entirely analogous to those for cylinders (eq. (2)) and plane parallel plates (eq. (3)) may now be written

$$\nu_r = \frac{d_r^2}{G_r D_i \tau_i} = \frac{\bar{c}_r}{c_0 \tau_i}$$

where G_r is the factor associated with the particular rectangular geometry considered and is a function of d_r/b_r, the width-to-length ratio of the rectangle. Thus, the condition that a given flame be quenched by both geometries under identical conditions is given by

$$\frac{d_p}{d_r} = \sqrt{\frac{G_p}{G_r}} = \sqrt{\frac{12}{G_r}} \tag{8}$$

The formal mathematical problem associated with equations (5) and (6) corresponds to other physical problems which have already been treated and which are presented by Jakob (ref. 4) and by Purday (ref. 5, pp. 16-18). The results given by these authors may be used to calculate values of c_r for a range of length-to-width ratios of the rectangular slot. The factor G_r may be evaluated as a function of (d_r/b_r) through the use of these values. The results may be fitted to a quadratic equation and used with equation (8) to give

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$$\frac{d_p}{d_r} = 1 - 0.300\left(\frac{d_r}{b_r}\right) - 0.047\left(\frac{d_r}{b_r}\right)^2 \tag{9}$$

Quenching by cylindrical annuli. - Proceeding in a similar manner, consider an annulus of infinite extent that is defined by two concentric cylinders of diameters a and b, where $a < b$ (fig. 1(d)). As before, let this annulus represent a region in which active particles are uniformly generated throughout the volume and destroyed on collision with the walls. The differential equation of diffusion describing this case is given in plane polar coordinates as

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dc}{dr}\right) + \frac{c_0}{D_1} = 0 \tag{10}$$

The boundary conditions are

$$\left.\begin{aligned} c &= 0 \\ r &= a/2 \end{aligned}\right\} \tag{11a}$$

and

$$\left.\begin{aligned} c &= 0 \\ r &= d_a/2 \end{aligned}\right\} \tag{11b}$$

It can be shown (ref. 6) that equation (10) has the solution

$$c = B_1 + B_2 \log_e r - \frac{1}{4}\frac{r^2 c_0}{D_1} \tag{12}$$

where B_1 and B_2 are arbitrary constants. Application of the boundary conditions gives

$$B_1 = \frac{1}{16D_i}\left[a^2c_0 - \frac{c_0(a^2 - d_a^2)\log_e (a/2)}{\log_e (a/d_a)}\right] \tag{13a}$$

and

$$B_2 = \frac{c_0(a^2 - d_a^2)}{16D_i \log_e (a/d_a)} \tag{13b}$$

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Thus

$$c = \frac{c_0}{16D_i}\left[(a^2 - 4r^2) + (d_a^2 - a^2)\frac{\log_e (a/2r)}{\log_e (a/d_a)}\right] \tag{14}$$

When a unit height is considered, the total number of active particles $C_{T,a}$ in the annulus is given by

$$C_{T,a} = \int_{a/2}^{d_a/2} c\ (2\pi r)\ dr \tag{15}$$

or

$$C_{T,a} = \frac{\pi c_0(d_a^2 - a^2)}{128\ D_i}\left[a^2 + d_a^2 + \frac{d_a^2 - a^2}{\log_e (a/d_a)}\right] \tag{16}$$

On the basis of the relations given for the reaction velocity (ref. 3), it follows that

$$\frac{C_{T,a}}{\tau_i} = \frac{c_0\pi}{4}(d_a^2 - a^2)\ \nu_a \tag{17}$$

Thus

$$\nu_a = \frac{1}{32D_i\tau_i}\left[(a^2 + d_a^2) + \frac{d_a^2 - a^2}{\log_e (a/d_a)}\right] \tag{18}$$

or

$$\nu_a = \frac{d_a^2}{32D_i\tau_i}\left[1 + \left(\frac{a}{d_a}\right)^2 + \frac{1 - (a/d_a)^2}{\log_e (a/d_a)}\right] \tag{19}$$

Thus, equations (2) and (19) give

$$\frac{d_c}{d_a} = \sqrt{1 + \left(\frac{a}{d_a}\right)^2 + \frac{1 - (a/d_a)^2}{\log_e (a/d_a)}} \tag{20}$$

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Equation (20) gives the relation between the quenching effect of an annulus and that of a cylinder in terms of the diameters and the diameter ratio of the cylindrical surfaces involved. As expected, $d_c = d_a$ for the case where $a = 0$.

Quenching by channels of elliptical and triangular cross section. - Calculations for any geometries other than those discussed previously may be carried out in a similar fashion. Thus, when a channel of elliptical cross section, where d_e and b_e are the minor and major axes, respectively, (fig. 1(e)) is considered, it follows from reference 5 (pp. 13 and 18) that the average chain length is given by

$$\nu_e = \frac{d_e^2}{16\left(\frac{d_e^2}{b_e^2} + 1\right) D_i \tau_i} \tag{21}$$

As expected, this equation reduces to equation (2) for the case where $d_e = b_e$.

Similarly, for a channel with a cross section defined by an equilateral triangle of side length d_t (fig. 1(f)), the results of reference 5 (p. 28) may be interpreted to give

$$\nu_t = \frac{d_t^2}{80 D_i \tau_i} \tag{22}$$

General relations. - The dimensional relation among the six quenching geometries treated may be expressed by the following set of equations:

$$\begin{aligned}
\frac{d_p^2}{12} = \frac{d_c^2}{32} = \frac{d_r^2}{12}\left[1 - 0.300\left(\frac{d_r}{b_r}\right) - 0.0470\left(\frac{d_r}{b_r}\right)^2\right]^2 \\
= \frac{d_a^2}{32}\left[1 + \left(\frac{a}{d_a}\right)^2 + \frac{1 - (a/d_a)^2}{\log_e (a/d_a)}\right] \\
= \frac{d_e^2}{32}\left[\frac{2}{1 + (d_e/b_e)^2}\right] \\
= \frac{d_t^2}{80}
\end{aligned} \tag{23}$$

APPARATUS

The apparatus consisted of a fuel-air metering-and-mixing system, a slot burner enclosed in a pressure-tight tank, and various inserts which were placed in the opening of the slot burner so as to alter the geometry of the burner channel. The sonic orifice propane-and-air metering system and the slot burner have been previously described (ref. 2). Consequently, discussion of the apparatus will be limited to the inserts used to modify the geometry of the burner channel.

Two types of slot burner insert were used: one type was designed to produce rectangular channels, the other to produce annular or cylindrical channels.

An example of the first type of insert is illustrated in figure 2(a). Two water-cooled brass blocks are placed in the opening of the slot burner in such a way as to produce a rectangular channel. Blocks of various dimensions were made in order to provide various rectangular channels. A spacer bar was made for each pair of water-cooled blocks. The bar had exactly the dimensions of the desired channel. The blocks, one on each side of the spacer bar, were placed in the slot burner and clamped tightly in place by the movable wall of the slot burner. The spacer bar was then removed, leaving a channel of the desired dimensions.

The kind of insert used to form channels of annular cross section is shown in figure 2(b). The cylindrical opening in the hollow brass block forms the outer diameter of the annulus. The removable centerbody forms the inner diameter of the annulus. Both the hollow block and centerbody were water cooled as shown. The position of the centerbody with respect to the cylindrical opening could be adjusted by means of the screws.

Exact axial alinement and centering of the centerbody is quite important, particularly when the difference between the inner and outer radii of the annulus is relatively small. As a device to aid proper situation of the centerbody, accurately machined brass sleeves were made to fit each of the annular channels. The wall thickness of each sleeve was made 0.002 inch less than the difference between the inner and outer radii of the corresponding annulus. The length of each sleeve was slightly greater than the length of the annular channel. These sleeves were used to center and to align the centerbody in the following way: The position of the centerbody was adjusted by the screws (fig. 2(b)) until the brass sleeve would slip easily into the entire length of the annular channel. Any slight misalinement of the centerbody was shown by sticking or jamming of the sleeve.

Very small centerbodies were made by joining 0.04- or 0.10-inch stainless-steel tubing to a short brass tube of large enough diameter to be conveniently held by the positioning screws. These small centerbodies were cooled by blowing air through them, so that it was necessary to extend the centerbody 10 to 12 inches above the burner lip to avoid disturbance of the flame by the air blast from the centerbody tip.

It was shown experimentally that exact centering of centerbodies which are small relative to the outer diameter of the annulus was much less critical than for larger centerbodies. Consequently, the 0.04- and 0.10-inch air-cooled centerbodies were centered visually, using a 0.25-inch inside-diameter sleeve as a guide. 3249

The insert used to form annular burner channels was also used to form cylindrical channels simply by removal of the centerbody. To obtain cylindrical channels of different diameters, brass sleeves were slipped into the cylindrical opening of the hollow block. The lips of such sleeves were water cooled.

PROCEDURE

The limiting pressure for flame propagation through a burner channel of any given geometry was measured in the same manner as described in reference 2. First, a flame was established on the burner. Then, after the combustion pressure was stabilized, flow to the burner was suddenly interrupted. The flame would either die on the burner lip, or flash back through the burner channel. Generally, the difference between the two pressures which defined the transition from the flash-back region to the quenching region could be determined to about 0.02 inch of mercury. Flash back occurred at the upper pressure, quenching at the lower. The limiting pressure was taken to be the average of these two pressures.

The question of whether or not air cooling provided sufficient cooling for the small (0.04 and 0.10 in.) centerbodies was resolved by decreasing stepwise the flow through the centerbody, measuring the limiting pressure after each step. The limiting pressure remained unchanged until the air flow was decreased to an exceedingly small fraction of the normally used flow. It was concluded that the method of cooling was satisfactory.

EXPERIMENTAL RESULTS

Experimental propane-air quenching data are recorded in table I for the three quenching geometries tested: quenching by rectangular slots, cylinders, and cylindrical annuli. Curves of limiting quenching pressure as a function of air-fuel ratio are presented in figure 3 for rectangular slots and in figures 4 and 5 for cylindrical annuli and cylinders. In these figures, an equivalence ratio scale φ, as well as a mass air-fuel ratio scale is given. Stoichiometric air-fuel ratio is indicated in each figure by a short vertical line placed just above the air-fuel scale. The range of φ values examined, 0.82 to 1.3, was deemed sufficiently large to serve the aims and purposes of this research and was actually narrower than the range that could have been obtained with the quenching apparatus for the 0.1-atmosphere to 1.0-atmosphere pressure range investigated.

DISCUSSION OF RESULTS

In order to compare the observed quenching behavior of the geometries investigated with that predicted by theory, the following approach was used. The full length (b_r, 5 in.) rectangular slot quenching distances need only small "end corrections" to be converted to quenching distances for plane parallel plates of infinite extent. Equation (9) was used to calculate reference plane parallel plate separation d_p values from the rectangular slot width d_r values for which the length-to-width ratio was greater than 10. The d_r values used and the reference d_p values calculated from them are indicated in figure 3(a). For a given air-fuel ratio, a logarithmic plot of these d_p values against limiting quenching pressure was then made and a straight line was obtained. For a given air-fuel ratio, this line (fig. 6) defines the reference d_p values with which the quenching behavior of all other geometries are compared. The "calculated" plane parallel plate quenching distance for any geometry was then defined to be that wall separation which would, according to equation (23), be as effective a quenching system as the geometry in question. These calculated values are indicated in figure 6 as data points.

A comparison of reference and calculated plane parallel plate quenching distances as a function of observed limiting pressures for cylinders, annuli, and rectangular slots is presented in figure 6 for air-fuel ratios of 19.0, 18.0, 15.6, 13.0, and 12.0. In figure 6, the straight lines are based only on the reference d_p values of figure 3(a).

The agreement of theory and experiment may be seen from the following table which presents the percentage deviation of calculated from reference plane parallel plate quenching distances for various geometries:

Mass ratio, A/F	Equivalence ratio, φ	Rectangular slot deviation, percent	Annulus deviation, percent	Cylinder deviation, percent
19.0	0.822	3.63	1.77	7.48
18.0	.867	3.96	2.39	7.91
15.6	1.00	6.16	3.99	7.07
13.0	1.20	8.50	5.99	6.57
12.0	1.30	11.12	11.33	5.07
$\varphi \leq 1$ range		4.58	2.72	7.48
$\varphi > 1$ range		9.81	8.66	5.82
Total range		6.67	5.09	6.86

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For rectangular slots and for cylindrical annuli, the agreement between theory and experiment improves systematically as the flame varies from rich to lean. For the case of quenching by cylinders, systematic improvement occurs when the flame is varied from lean to rich. In practically all cases, however, the deviation of the calculated from the reference plane parallel plate quenching distance appears to depend upon the air-fuel ratio. This deviation may be interpreted to mean that the term

$$\frac{d^2}{G} = \frac{A}{k_i}\left(\frac{T_R}{T_O}\right)^n \left(\frac{1}{N_f \sum\limits_i \frac{p_i}{D_i}}\right)$$

of equation (1) varies slightly with geometry and that the amount of this variation is mildly air-fuel-ratio dependent.

Examination of the data of figure 6 indicates that the individual deviations for any geometry practically always have the same algebraic sign. Allowing for a small amount of experimental scatter, it is apparent that the calculated plane parallel plate quenching distances for annuli are somewhat larger than anticipated and that those for rectangular slots and cylinders are somewhat smaller than anticipated. This may again be interpreted as meaning that the term d^2/G varies slightly with geometry.

Good agreement between calculated and reference d_p values is obtained even for values of $\varphi > 1$ (A/F < 15.6). Because equation (1) does not appear to be entirely suitable for values of $\varphi > 1$ (ref. 2), this agreement may be attributed to the fact that all terms other than d and G essentially cancel out in the course of the calculations.

The fact that a relatively small cold surface may exhibit a large quenching effect, under proper circumstances, is supported both by theory and experiment. Thus, equation (20) may be used to predict that when a 0.04-inch-outside-diameter cold tube is inserted along the axis of a 1-inch-inside-diameter tube, the unit will quench as effectively as a 0.83-inch-inside-diameter cylindrical tube. The observed effect is even larger than that predicted, and the unit quenches as effectively as a 0.75-inch-inside-diameter cylindrical tube. This large effect may be explained by the fact that even a small surface can serve as a large sink for active particles (fig. 7). Thus, a small centerbody changes the active-particle concentration field from one with a relative maximum at the center for the cylinder to zero throughout the centerbody for an annulus (fig. 7). The average concentration of active particles in the channel is thereby sufficiently lowered to cause a large increase in the quenching effect of the unit.

It has been indicated (ref. 2) that the effect of geometry on quenching predicted on the basis of the average chain length calculations may also be predicted through the use of a thermal quenching equation in which the propagation or nonpropagation of a flame is determined by some critical value of the average reaction temperature excess. Thus, figure 7 may also represent the change in the reaction temperature field from one with a maximum at the center for the cylinder to cold gas temperature throughout the centerbody for the annulus.

It is interesting to note what the preceding analysis suggests for the quenching of flames whose propagation is not governed solely by simple diffusion (or conduction) processes. Thus, for a turbulent flame, a cold centerbody introduced along the axis of a cylinder may serve as an even larger sink for active particles (or for heat) than it does in the laminar case.

SUMMARY OF RESULTS

The following observations were made during the investigation of channel geometry effect on quenching laminar flames:

1. The effect of geometry on flame quenching may be calculated for plane parallel plates of infinite extent, cylindrical tubes, rectangular slots, cylindrical annuli, and tubes of elliptical and equilaterally triangular shape by use of the following set of equations:

$$\frac{d_p^2}{12} = \frac{d_c^2}{32} = \frac{d_r^2}{12}\left[1 - 0.300\left(\frac{d_r}{b_r}\right) - 0.047\left(\frac{d_r}{b_r}\right)^2\right]^2$$

$$= \frac{d_a^2}{32}\left[1 + \left(\frac{a}{d_a}\right)^2 + \frac{1 - (a/d_a)^2}{\log_e (a/d_a)}\right]$$

$$= \frac{d_e^2}{32}\left[\frac{2}{1 + (d_e/b_e)^2}\right]$$

$$= \frac{d_t^2}{80}$$

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where

a inside annulus diameter

b_e ellipse major axis

b_r rectangular slot length

d_a outer diameter of annulus

d_c cylinder diameter

d_e minor axis of ellipse

d_p plane parallel plate separation

d_r rectangular slot width

d_t side length of equilateral triangle

2. Flame-quenching data for propane-air flames by means of a series of rectangular slots, cylinders, and cylindrical annuli were obtained for a range of pressures and air-fuel ratios.

3. The average deviation of the predicted quenching distances from the observed ones is 4.3 percent for equivalence ratios less than or equal to unity and 8.6 percent for equivalence ratios greater than unity. These deviations are generally systematic, rather than random.

4. Relatively small cold surfaces may, when flame immersed, exhibit very large quenching effects. Thus, a 0.04-inch-outside-diameter cold tube when inserted along the axis of a 1-inch-inside-diameter tube will cause the unit to quench as effectively as a 0.75-inch-inside-diameter cylinder.

CONCLUSIONS

The following conclusions were drawn from the investigation:

1. The observed variation of flame quenching as a function of quenching geometry may be successfully predicted for a range of pressures and for rich as well as lean propane-air flames.

2. The increased quenching effect brought about through the introduction of a cold surface into a bounded flame is essentially determined by how large a sink (for heat or for active particles) the surface is. Thus, a small appropriately placed cold surface may exhibit a large quenching effect.

Lewis Flight Propulsion Laboratory
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TABLE I. - PROPANE-AIR QUENCHING DATA FOR RECTANGULAR SLOTS, CYLINDERS, AND CYLINDRICAL ANNULI

(a) Rectangular slots

Width, d_r, in.	Length, b_r, in.	Air-fuel ratio, A/F	Pressure, P, atm	Width, d_r, in.	Length, b_r, in.	Air-fuel ratio, A/F	Pressure, P, atm	Width, d_r, in.	Length, b_r, in.	Air-fuel ratio, A/F	Pressure, P, atm
0.255	0.250	18.99	0.4665	0.255	0.750	13.77	0.2674	0.510	1.499	11.83	0.1427
		17.93	.4294			12.84	.2794	.150	5.000	19.00	.6082
		16.95	.3927			11.81	.3095			18.24	.5581
		15.92	.3696	.510	.500	18.93	.2206			17.36	.5207
		15.91	.3706			18.92	.2306			16.47	.4873
		14.86	.3539			18.25	.2062			15.36	.4569
		13.86	.3492			17.94	.2052			14.34	.4462
		13.84	.3486			16.89	.1878			13.26	.4512
		12.80	.3573			15.92	.1775			12.21	.4689
		11.79	.3830			15.92	.1738			11.40	.5113
		11.77	.3833			14.89	.1708	.255		18.97	.3108
	.375	18.93	.3964			13.86	.1694			17.96	.2894
		17.93	.3543			13.81	.1671			16.98	.2727
		16.97	.3302			12.86	.1734			15.97	.2610
		16.96	.3312			12.86	.1714			14.88	.2547
		15.98	.3095			11.83	.1801			13.85	.2567
		14.86	.2978			11.80	.1841			12.91	.2717
		14.84	.2984			11.75	.1828			11.63	.3195
		13.86	.2928		.750	18.95	.1808	.340		18.88	.2236
		13.81	.2938			17.92	.1654			17.97	.2062
		13.80	.2944			17.78	.1654			16.99	.1968
		12.80	.3028			17.01	.1567			16.94	.1962
		11.78	.3242			15.95	.1494			15.94	.1878
		11.75	.3285			14.92	.1440			15.86	.1888
	.750	18.94	.3509			14.86	.1440			14.89	.1845
		18.87	.3385			13.88	.1434			13.81	.1865
		17.96	.3158			12.83	.1467			13.41	.1905
		17.91	.3091			11.77	.1564			12.36	.2025
		17.02	.2914		1.499	18.12	.1440	.510		18.55	.1357
		17.01	.2891			17.98	.1454			17.61	.1290
		15.93	.2747			16.97	.1369			16.62	.1227
		15.91	.2760			15.97	.1300			15.61	.1220
		14.90	.2677			14.91	.1267			14.57	.1186
		14.87	.2664			13.85	.1267			13.58	.1206
		13.88	.2650			12.84	.1313			12.59	.1283

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TABLE I. - Continued. PROPANE-AIR QUENCHING DATA FOR RECTANGULAR SLOTS, CYLINDERS, AND CYLINDRICAL ANNULI

(b) Cylinders

Diameter, d_c, in.	Air-fuel ratio, A/F	Pressure, P, atm	Diameter, d_c, in.	Air-fuel ratio, A/F	Pressure, P, atm
0.252	18.99	0.4853	0.750	16.02	0.1223
	17.93	.4442		15.92	.1227
	17.04	.4208		14.94	.1210
	15.98	.4051		14.89	.1216
	14.91	.3944		14.86	.1219
	14.83	.3934		13.89	.1223
	13.96	.3954		12.89	.1277
	13.85	.3940		12.81	.1287
	12.84	.4114		11.83	.1420
	11.79	.4669	1.000	18.98	.0999
.499	18.99	.2232		17.95	.0949
	18.92	.2229		17.90	.0953
	17.99	.2072		16.88	.0909
	16.98	.1972		15.94	.0896
	15.94	.1915		15.28	.0879
	15.92	.1918		14.93	.0886
	14.90	.1885		13.84	.0896
	13.91	.1898		12.78	.0946
	12.82	.1992		12.09	.1029
	11.84	.2232		11.76	.1029
	11.79	.2232			
.750	19.26	.1450			
	18.04	.1350			
	17.95	.1333			
	17.03	.1280			

TABLE I. - Concluded. PROPANE-AIR QUENCHING DATA FOR RECTANGULAR SLOTS, CYLINDERS, AND CYLINDRICAL ANNULI

(c) Cylindrical annuli

d_a in.	Inside diameter, a, in.	Air-fuel ratio, A/F	Pressure, P, atm	d_a in.	Inside diameter, a, in.	Air-fuel ratio, A/F	Pressure, P, atm	d_a in.	Inside diameter, a, in.	Air-fuel ratio, A/F	Pressure, P, atm
0.750	0.040	18.89	0.1945	1.000	0.040	17.00	0.1240	1.000	0.498	17.02	0.2714
		17.86	.1831			16.93	.1243			16.93	.2697
		16.98	.1748			15.90	.1213			15.91	.2623
		16.93	.1746			14.94	.1200			14.97	.2583
		15.85	.1701			14.80	.1203			14.91	.2597
		14.91	.1701			13.80	.1230			14.84	.2603
		14.76	.1698			13.78	.1227			13.81	.2694
		13.84	.1721			12.80	.1313			13.78	.2640
		12.86	.1854			12.75	.1327			12.82	.2871
		12.76	.1902			11.72	.1527			11.79	.3469
		11.81	.2105			11.72	.1574		.626	18.98	.4505
	.250	18.95	.3081		.100	18.99	.1544			18.02	.4161
		18.89	.3068			18.99	.1534			16.97	.3867
		17.89	.2847			18.04	.1457			16.93	.3823
		16.96	.2727			17.04	.1377			15.95	.3683
		16.95	.2717			17.00	.1390			14.88	.3559
		15.82	.2587			15.98	.1347			14.96	.3566
		14.74	.2583			15.96	.1330			13.84	.3553
		13.86	.2603			14.90	.1337			13.76	.3543
		13.81	.2627			14.89	.1337			12.85	.3690
		12.78	.2891			13.84	.1384			12.84	.3703
		11.83	.3372			12.84	.1501			11.80	.4087
		11.79	.3375			12.81	.1481		.750	18.93	.6577
	.498	18.90	.6844			11.83	.1684			17.97	.6106
		17.86	.6310		.250	18.97	.1888			17.01	.5845
		16.90	.5939			17.98	.1765			16.94	.5818
		15.86	.5758			17.89	.1761			15.98	.5605
		15.76	.5768			17.06	.1683			14.93	.5541
		74.78	.5701			15.95	.1638			14.88	.5551
		14.77	.5708			14.89	.1621			14.40	.5534
		13.82	.5648			13.82	.1664			14.32	.5554
		12.80	.5999			13.80	.1661			13.84	.5544
		12.70	.6002			12.83	.1848			13.82	.5521
		11.87	.7299			11.84	.2115			12.84	.6193
		11.77	.7299			11.78	.2122			12.83	.6213
1.000	.040	18.95	.1374		.498	18.99	.3014			12.81	.6256
		18.89	.1367			17.98	.2837			11.83	.7242
		17.91	.1287							11.77	.7269

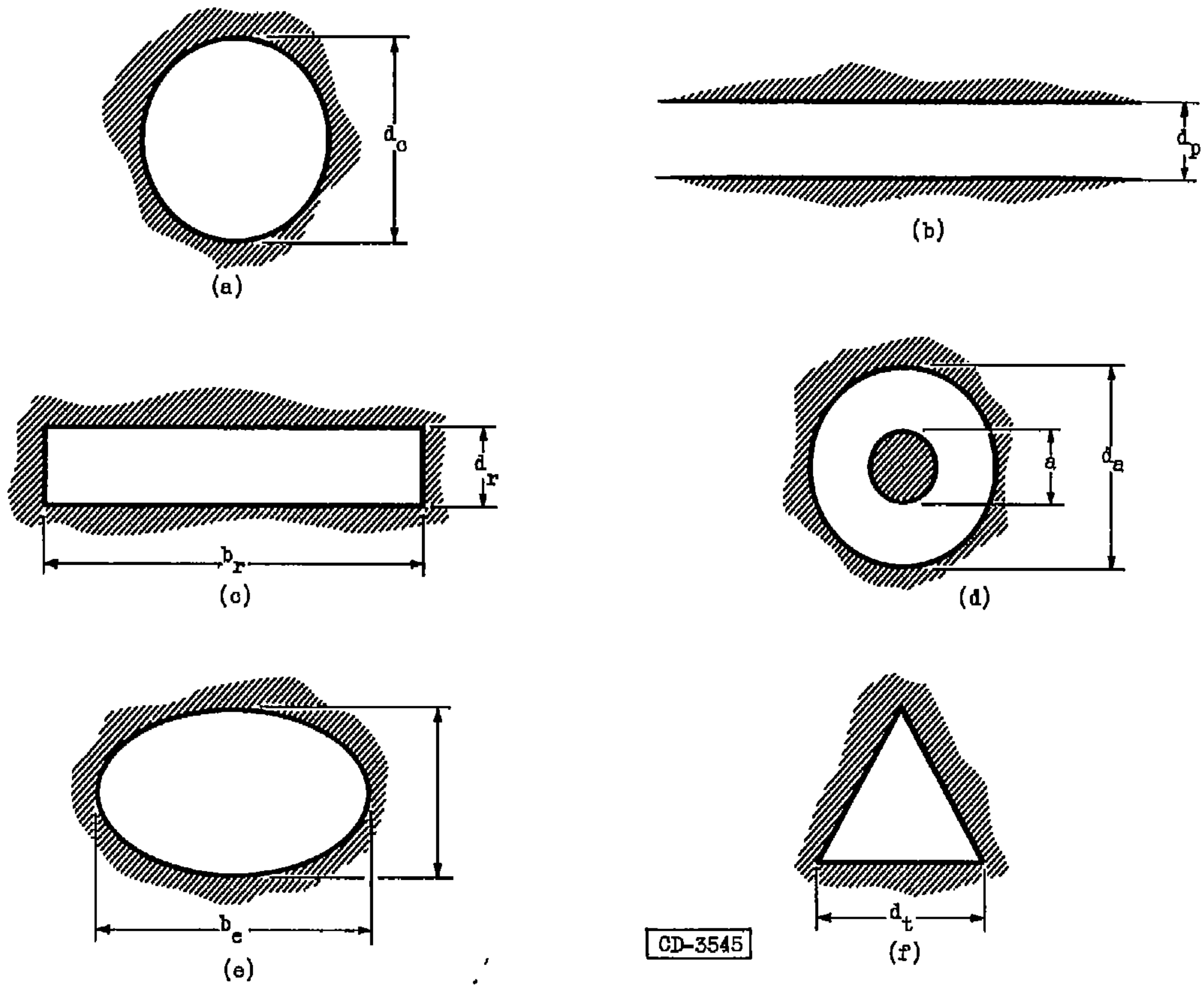
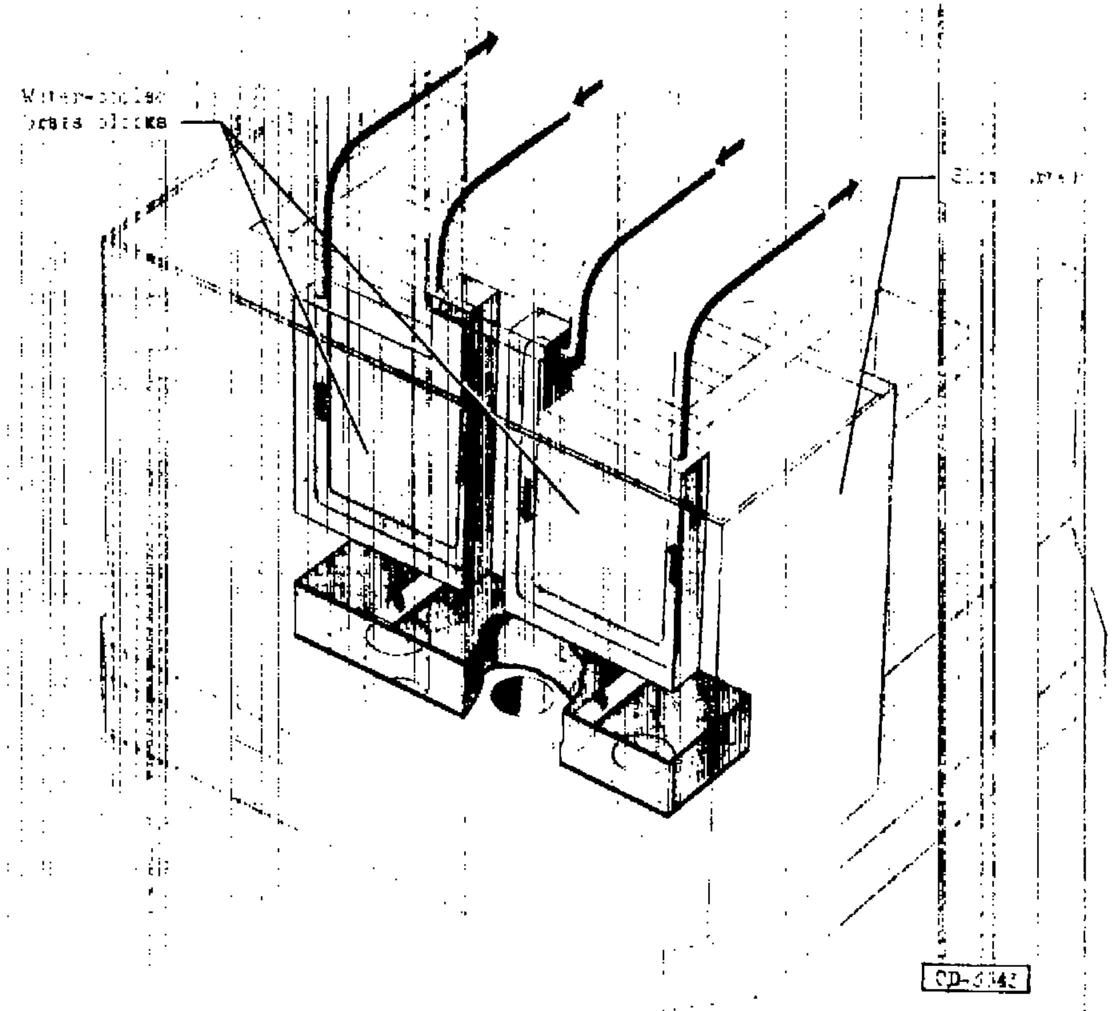
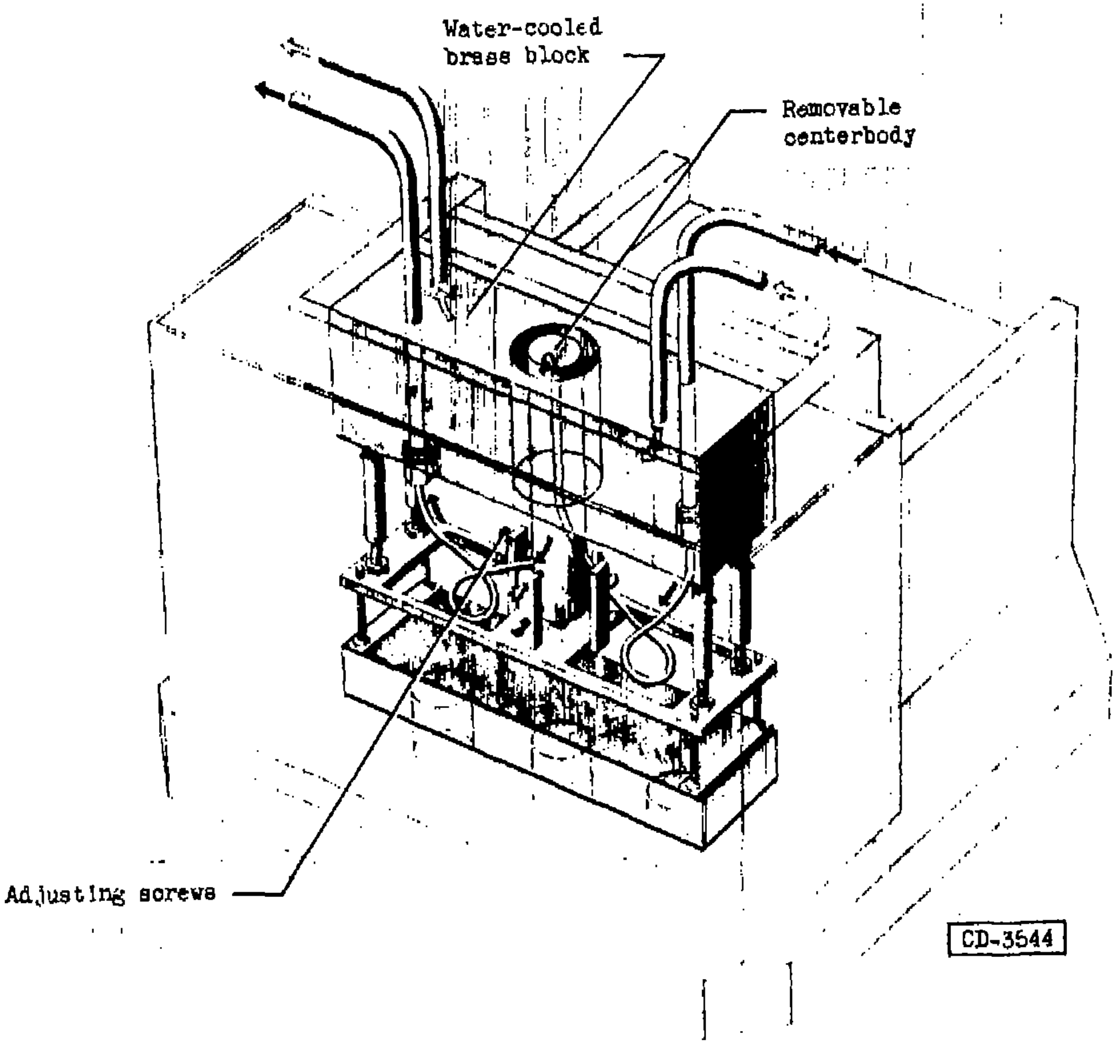


Figure 1. - Quenching geometries.



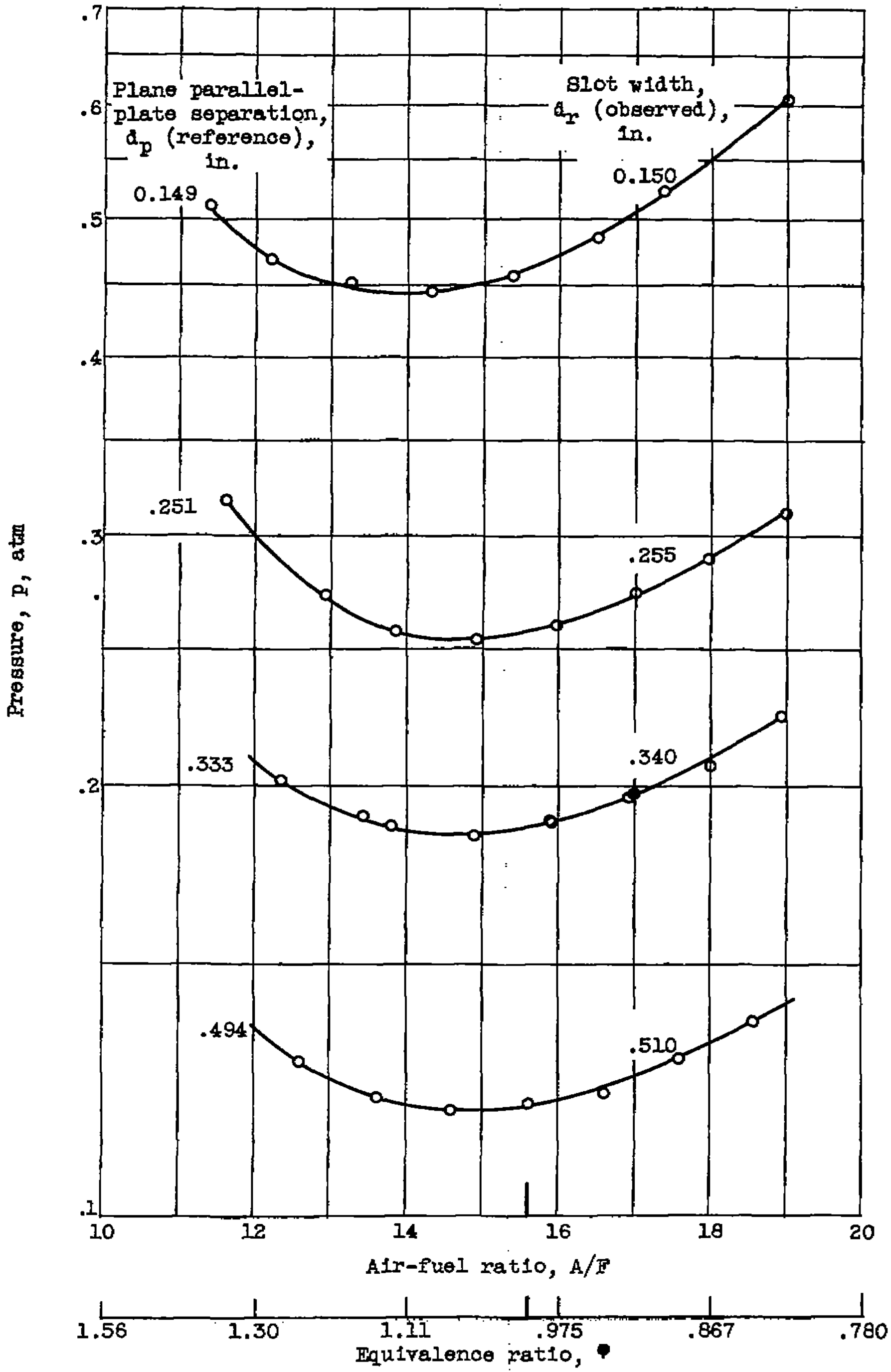
(a) Rectangular insert.

Figure 2. - Slot burner with insert.



(b) Annular insert.

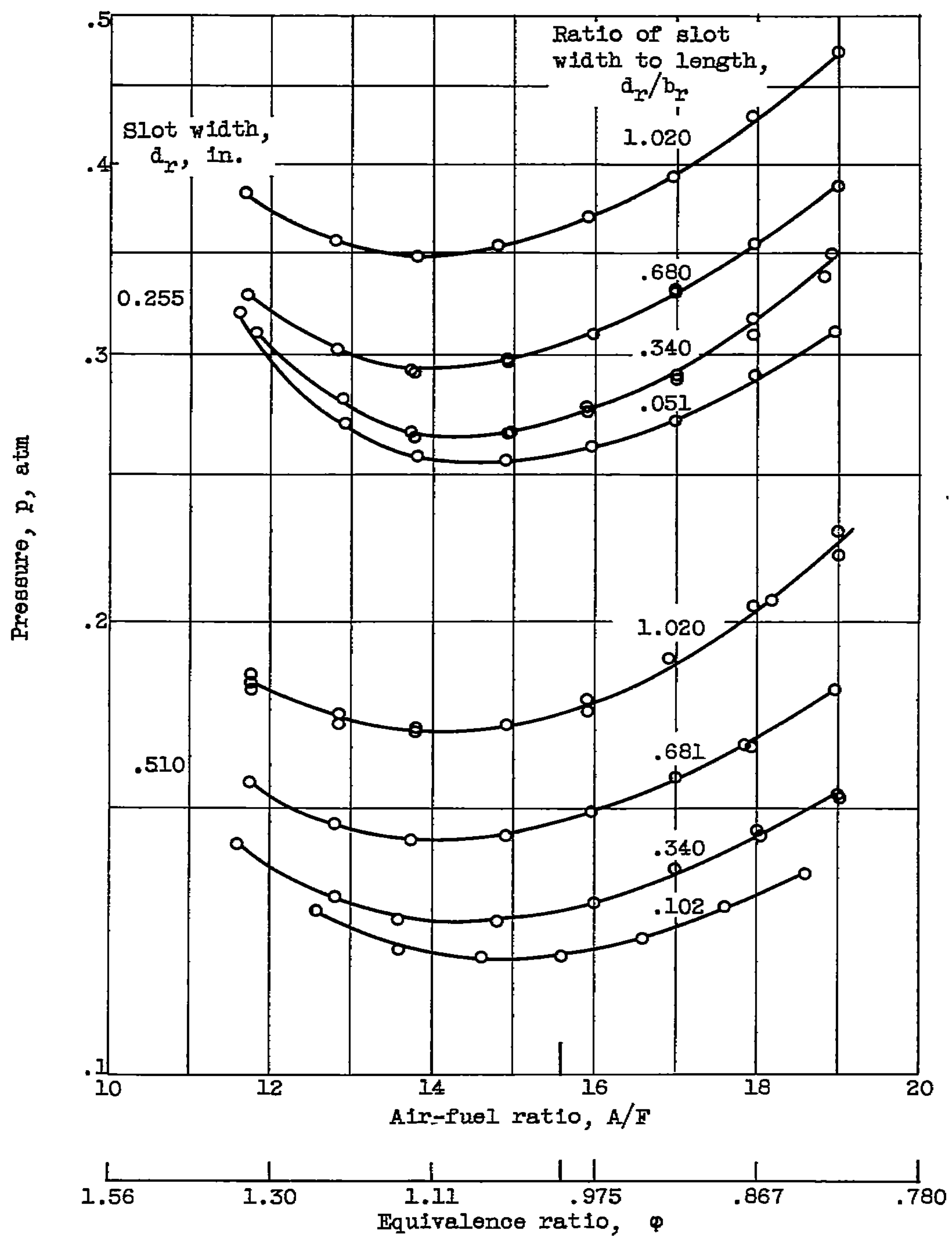
Figure 2. - Concluded. Slot burner with insert.



(a) Full length (5 in.) slots of various widths.

Figure 3. - Limiting pressure curves for various series of rectangular slots.

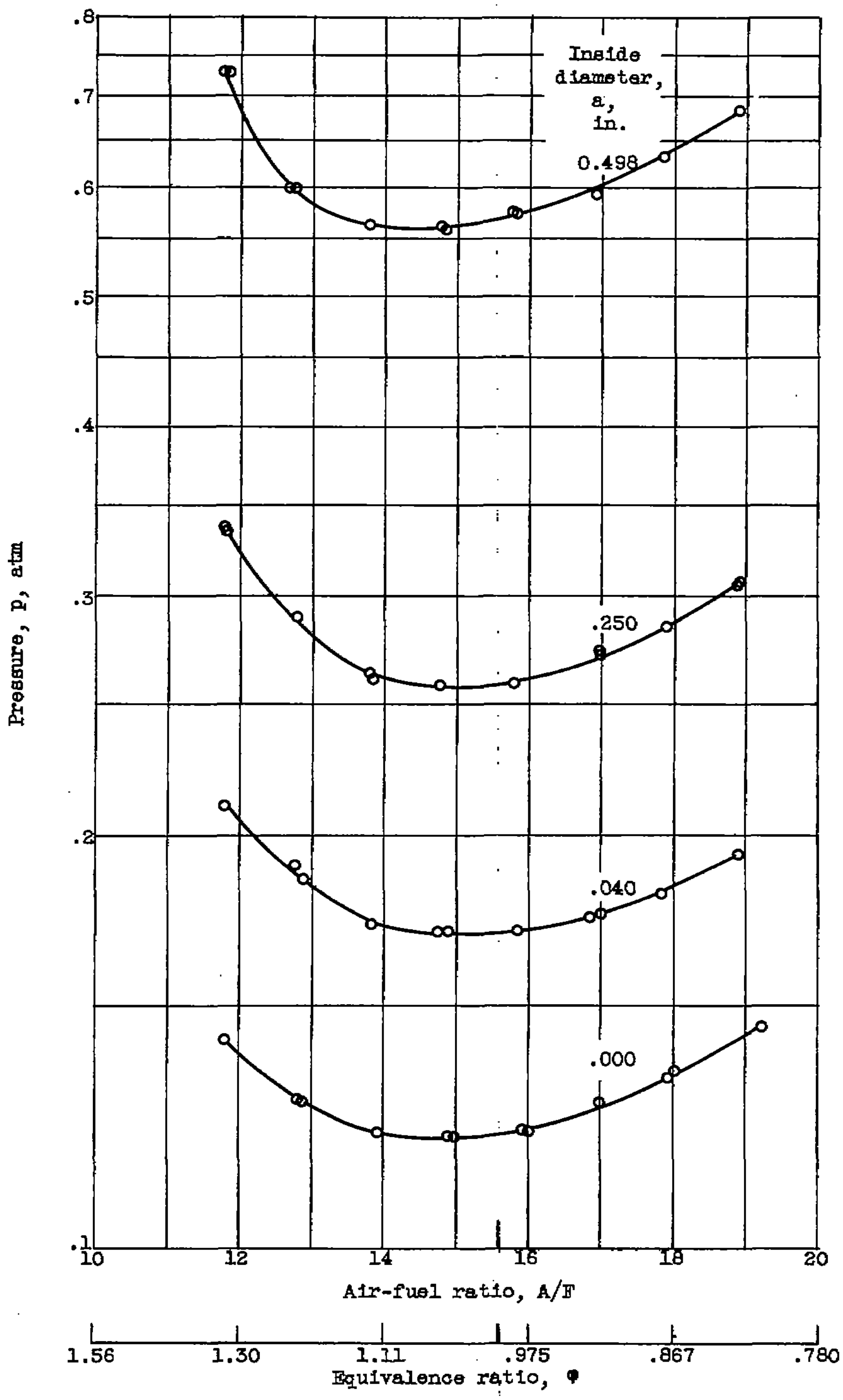
3249



(b) Slots of various lengths and widths.

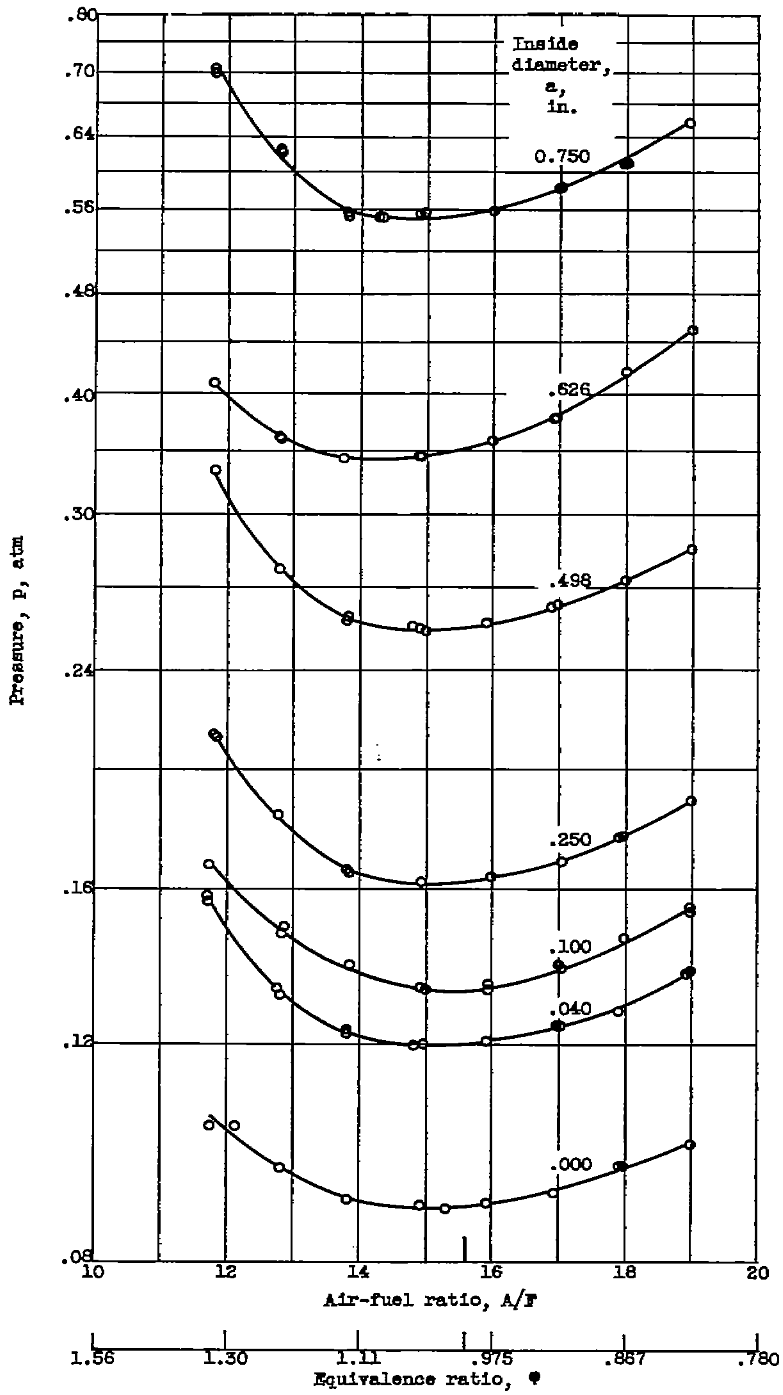
Figure 3. - Concluded. Limiting pressure curves for various series of rectangular slots.

3249



(a) Outside diameter, 0.750 in.

Figure 4. - Limiting pressure curves for two series of annuli.



(b) Outside diameter, 1.000 in.

Figure 4. - Concluded. Limiting pressure curves for two series of annuli.

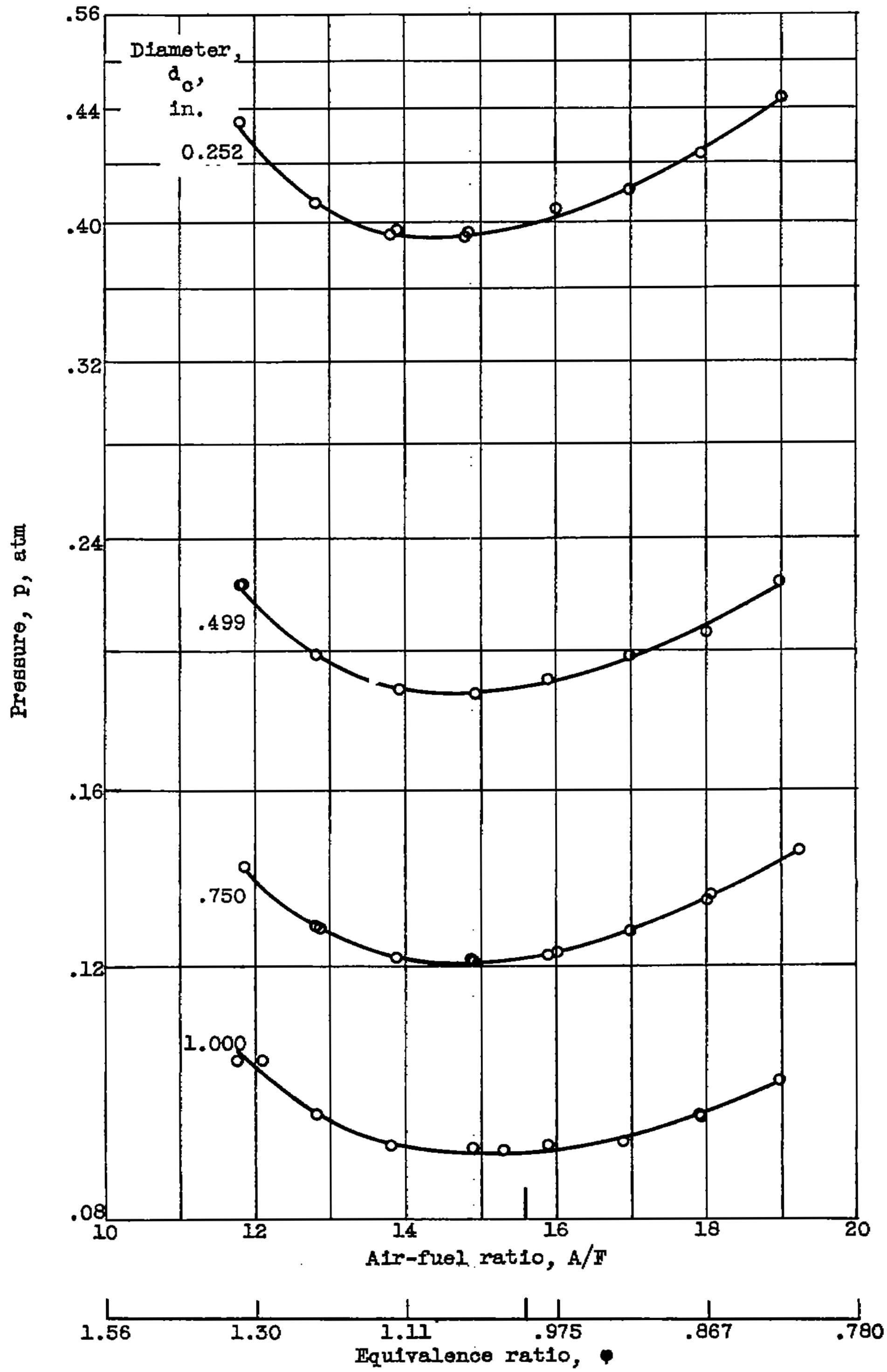
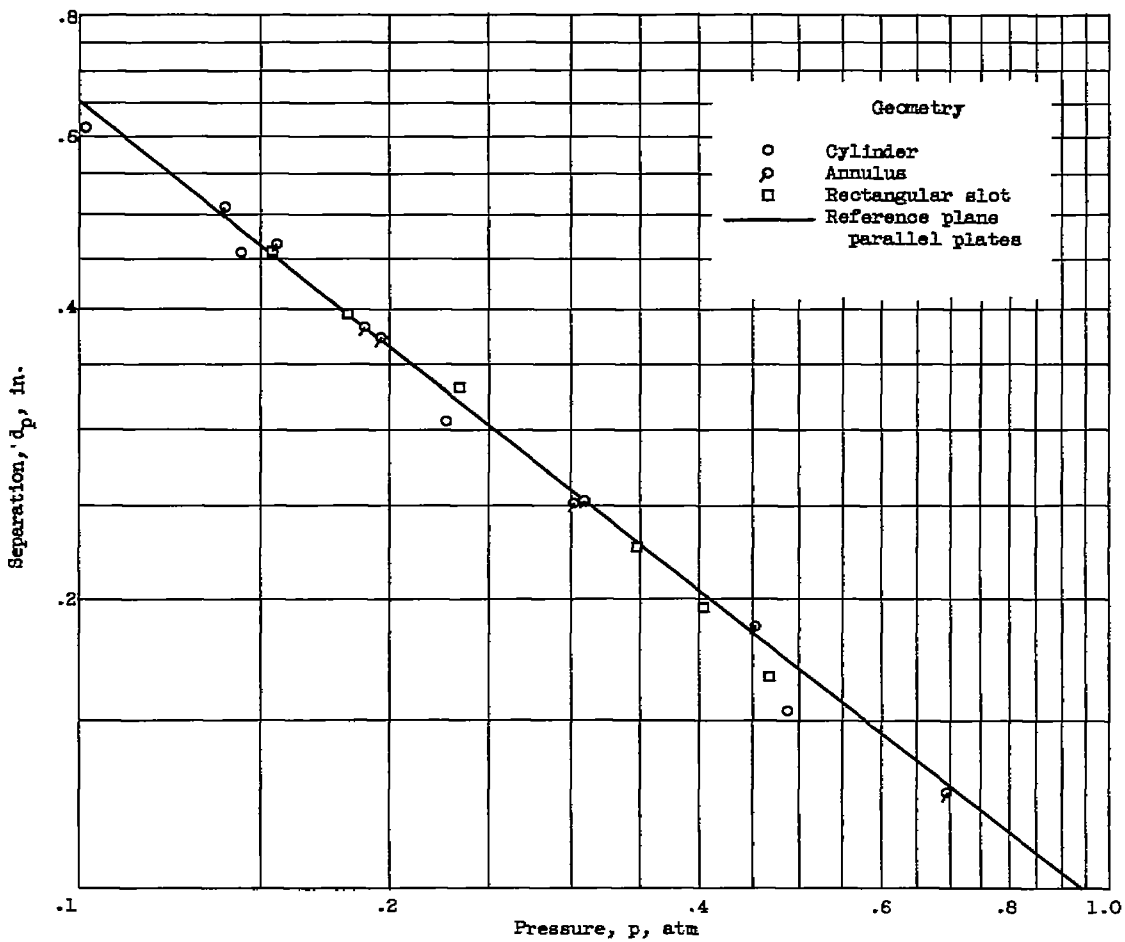
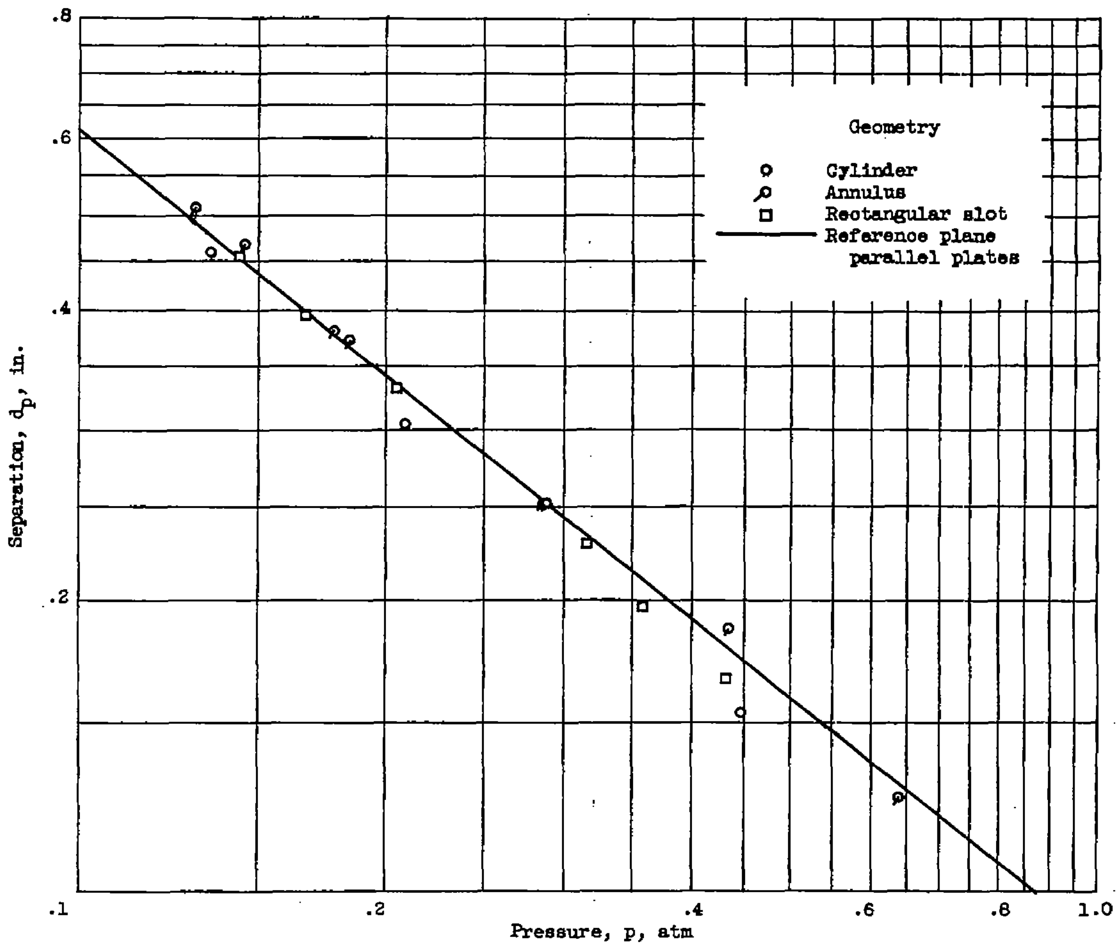


Figure 5. - Limiting pressure curves for series of cylinders.



(a) Air-fuel ratio, 19.0.

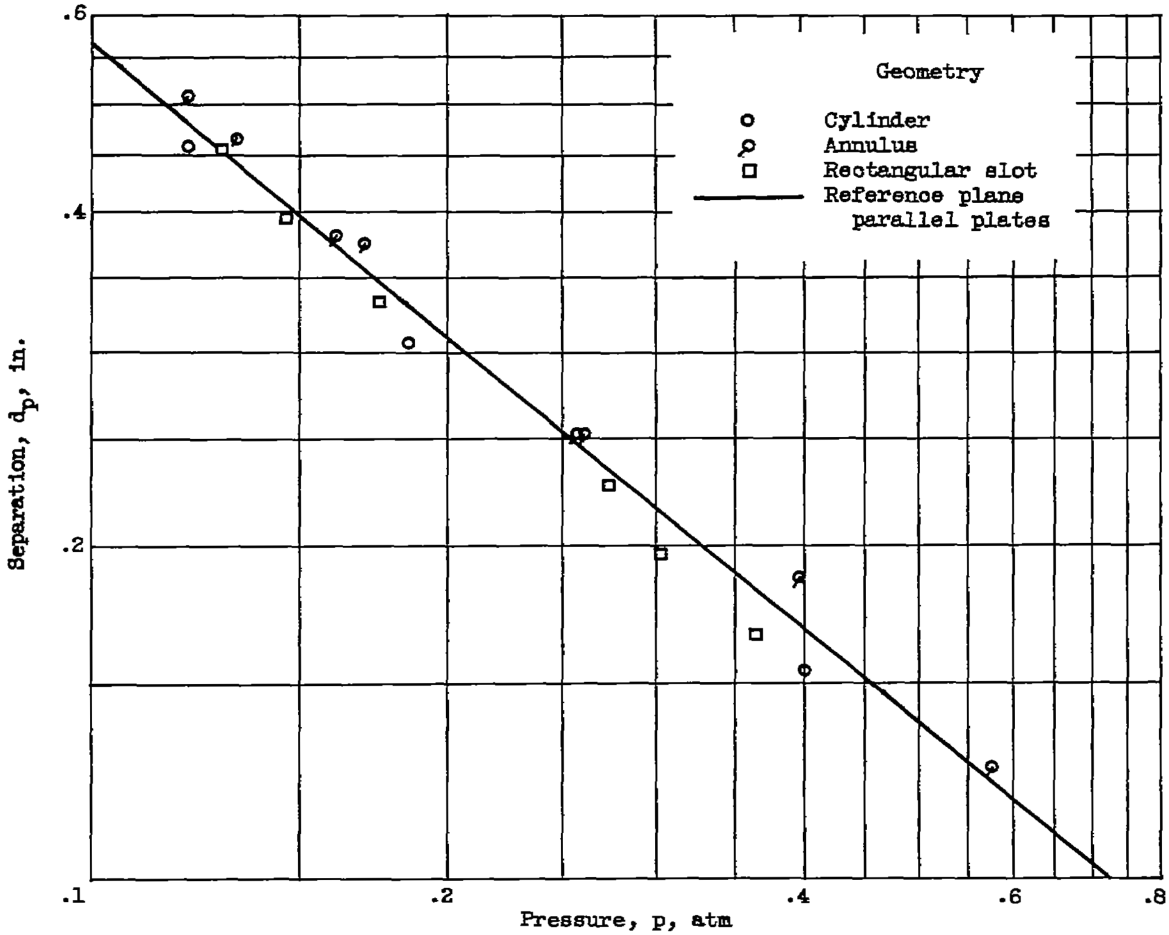
Figure 6. - Calculated plane parallel plate quenching distance as a function of observed limiting pressure for various geometries.



(b) Air-fuel ratio, 18.0.

Figure 6. - Continued. Calculated plane parallel plate quenching distance as a function of observed limiting pressure for various geometries.

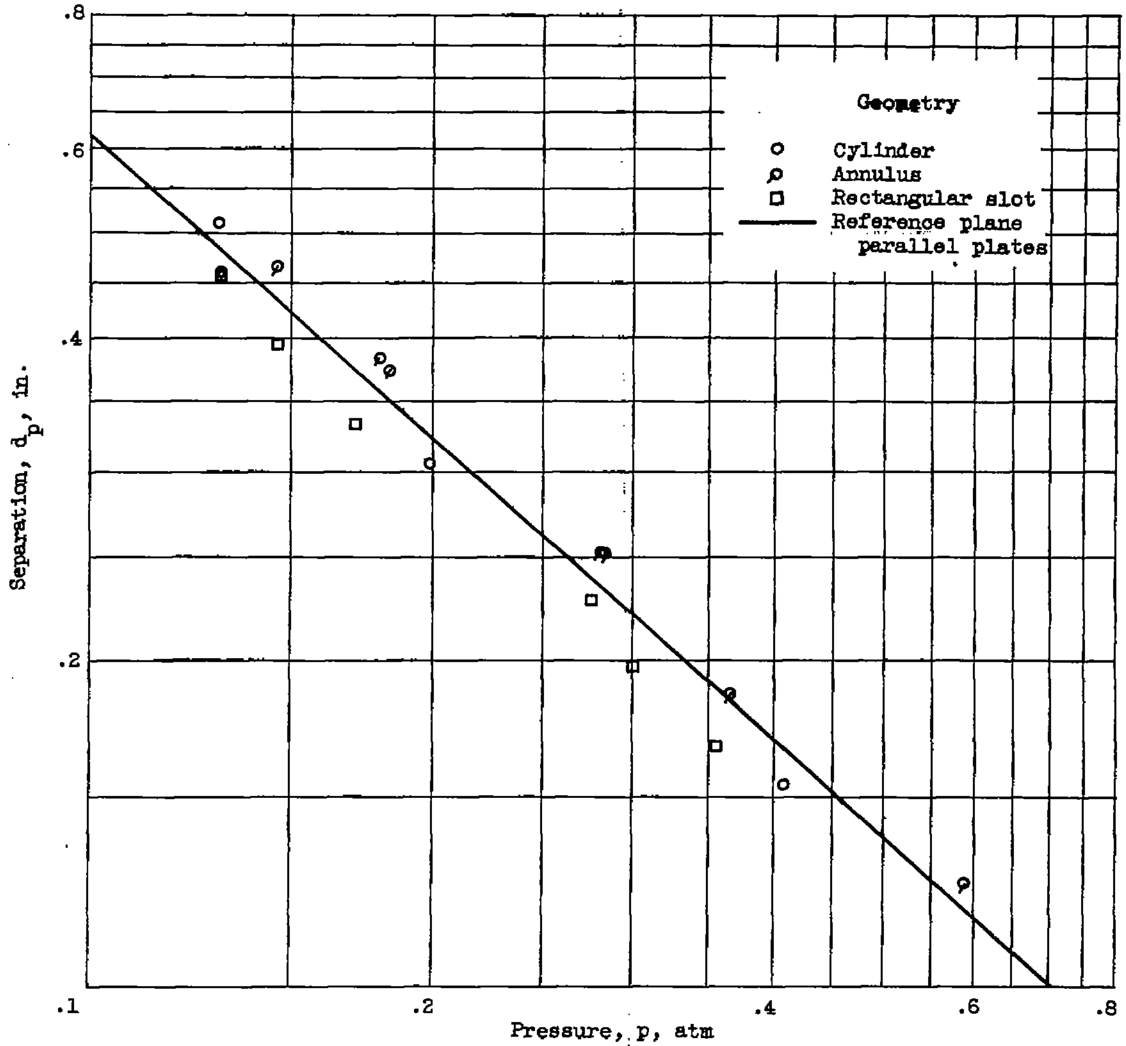
3249



(c) Air-fuel ratio, 15.6.

Figure 6. - Continued. Calculated plane parallel plate quenching distance as a function of observed limiting pressure for various geometries.

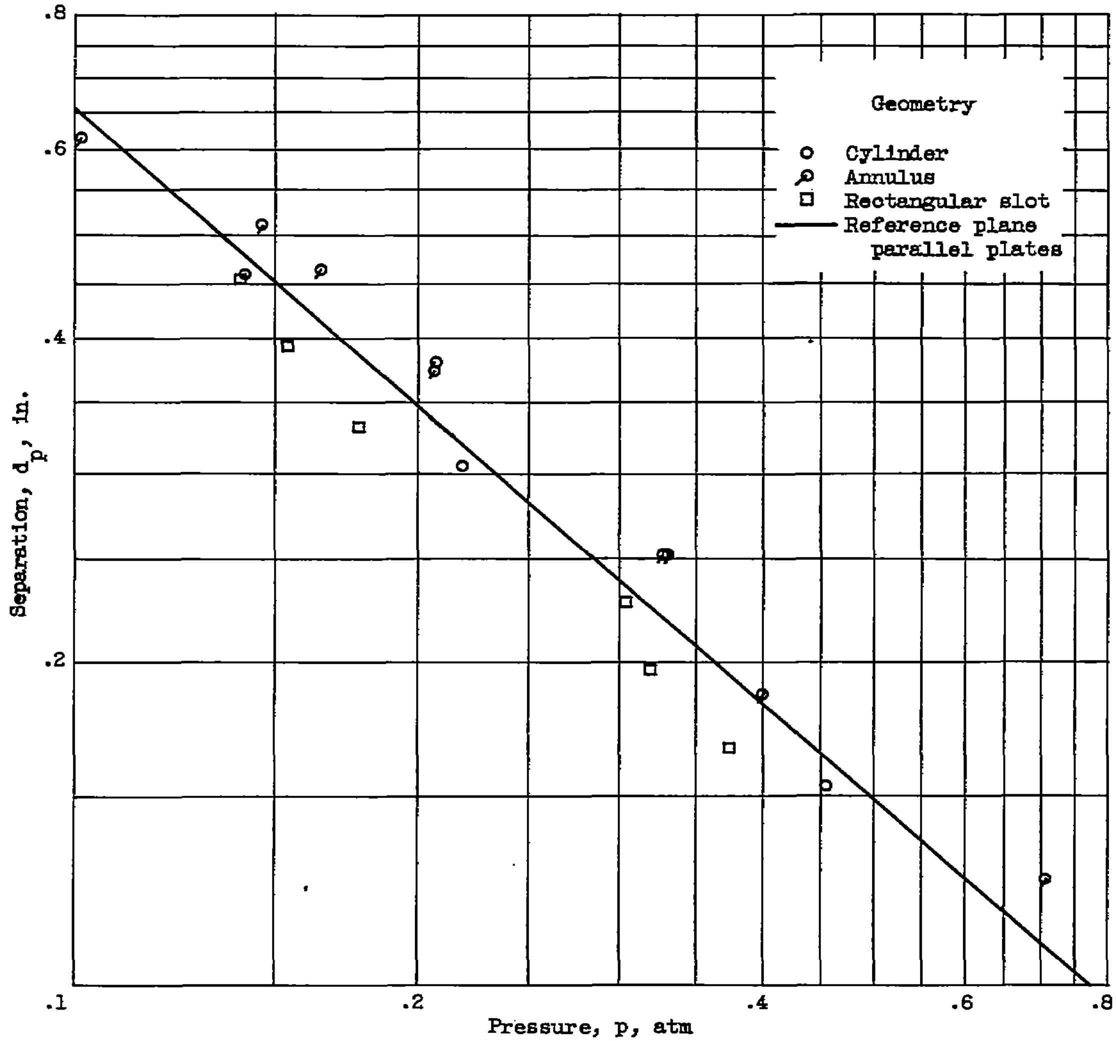
3249



(d) Air-fuel ratio, 13.0.

Figure 6. - Continued. Calculated plane parallel plate quenching distance as a function of observed limiting pressure for various geometries.

3249



(e) Air-fuel ratio, 12.0.

Figure 6. - Concluded. Calculated plane parallel plate quenching distance as a function of observed limiting pressure for various geometries.

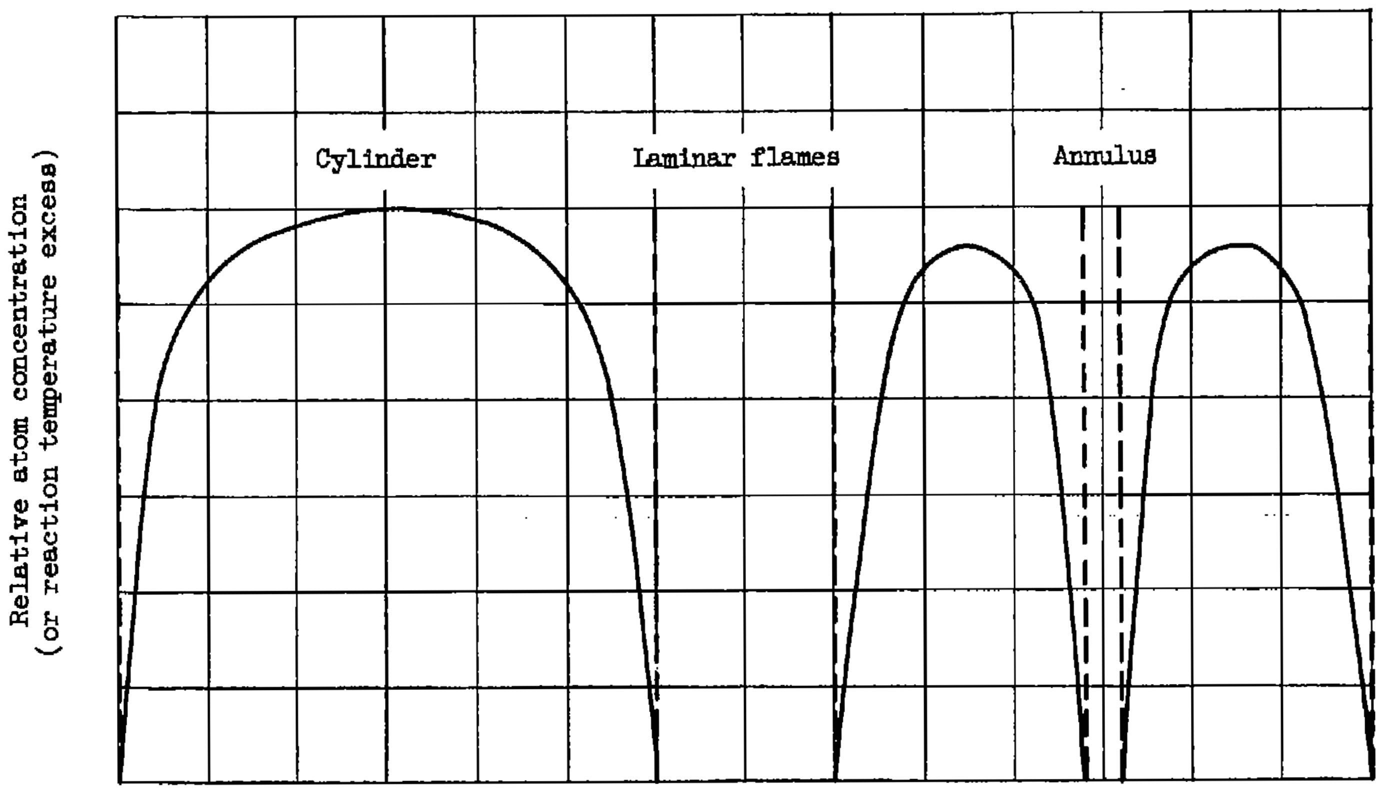


Figure 7. - Relative atom concentration (or reaction temperature excess) as function of position in cylinder and annulus for typical case of laminar flame propagation (qualitative representation).